The science scope of the HED instrument focuses on states of matter at high density, temperature, pressure, electric and/or magnetic field. Major applications are high-pressure planetary physics, warm- and hot- dense matter, laser-driven relativistic plasmas and complex solids in pulsed magnetic fields. These extreme states can be reached by different types of optical lasers, the X-ray FEL beam and pulsed coils. User operation at the HED instrument is foreseen to start in Q2 2019.

### Properties of XFEL undulator for HED (SASE2)

- **SASE2 undulator**
  - Hard X-ray source: 3 – 25 keV photon energy, 10³ SASE bandwidth, 10⁴ self-seeded
  - Repetition rate: 10 Hz bunch trains with up to 2700 pulses
  - Pulse energy: 10⁻³ – 10⁻² X-ray photons per pulse / 100 nJ – few mJ
  - Pulse duration: 2 to 100 fs (correlates with bunch charge)
- **HED instrument X-ray optics & beam characteristics**
  - Three mirrors (two for beam offset & one for distribution between HED / MID instruments)
  - Monochromators: 4-bounce Si₁₁₁ (5 – 25 keV, ~10⁶), high-resolution monochromator (~10⁵)
  - Focusing: Bragg lenses at three positions (229, 887 and 982 m downstream of the undulator exit) resulting in spot sizes of ~200 μm, ~20 μm, and 1 – 3 μm FWHM for 5 – 25 keV
  - Split & Delay Line (BMBF project, U Münster): Delays: ~2 ps (20 keV) to ~23 ps (5 keV)
- **Replication rate**
  - 4.5 MHz, 1 – 10 Hz, shot-on-demand

### Optical “drivers”: intense lasers

- **Pump-probe (PP) laser** (XFEL/EU)
  - 0.05 – 2 mJ, 4.5 – 0.1 MHz, 15 fs, λ = 800 nm
  - 1 – 40 mJ, 4.5 – 0.1 MHz, 900 fs, λ = 1030 nm
- **100 – 200 TW short-pulse laser** (HIBEF UC)
  - 4–10 J, 25 fs, 10 Hz, 740 – 860 nm, ø145 mm
- **DIPOLE100-X, 100 J long-pulse laser** (HIBEF UC)
  - 100 J, 2 - 15 ns, 10 Hz, 1030 nm
  - 75 mm × 75 mm square beam profile
- **Optical diagnostics** (XFEL EU & HIBEF)
  - VISAR, SOP & FDI

### X-ray diagnostics available at HED

- **X-ray diffraction**
  - IC1: gain-switching in-vacuum tiled detectors (ePIX 100, Jungfrau), motorized
  - IC1 and IC2: large area detectors in air (or in air pocket in vacuum) Perkin-Elmer
eAgAs AGIDP on detector bench with central hole (220-mm framing to record bunch pattern)

- **Inelastic X-ray scattering**
  - Two HAPG Harms spectrometers (/E ≤ 9 eV) on motorized rails on vertical breadboard

- **Spherical dinned Si (533) analyzers for E/A = 10⁵ high resolution inelastic x-ray scattering**

- **X-ray absorption spectroscopy**
  - Bent Si crystal spectrometers before IC1.

- **HED Interaction chamber “IC1”**
  - Circular rails for mounting detectors, spectrometers or analysers crystals fitted to a vertical breadboard.
  - All-aluminium chamber to avoid activation during relativistic laser-plasma experiments.
  - Built by Toyama, Japan. Installed in May 2017.
  - Some beam paths of the optical lasers inside the chamber IC1. All mirrors are adjustable in position and angle.

- **Beam stop**
  - Interaction chamber IC1

### X-ray detectors

- **Parameters**
  - *ePix100 (SLAC)*
    - Sensor: 300 μm Si
    - Sensor size: 704 × 768 (20k e/s)
    - Frame rate: 384 (20k e/s)
    - Number of pixels: 1024 × 1024
    - Resolution: 1.25 (25 e/s)
  - *ePix10k (SLAC)*
    - Sensor: 120 μm Si
    - Sensor size: 3840 × 3072 (100k e/s)
    - Frame rate: 750 (200k e/s)
    - Number of pixels: 1280 × 1024
    - Resolution: 0.125 (100k e/s)
  - *Jungfrau (PSI)*
    - Sensor: 320 μm Si
    - Sensor size: 2048 × 1280 (400k e/s)
    - Frame rate: 1280 (800k e/s)
    - Number of pixels: 384000
    - Resolution: 0.125 (100k e/s)
  - *Gotthard-I (PSI)*
    - Sensor: 320 μm Si
    - Sensor size: 2048 × 1280 (400k e/s)
    - Frame rate: 1280 (800k e/s)
    - Number of pixels: 384000
    - Resolution: 0.125 (100k e/s)

- **Pixel size (μm)**
  - 760 (12 μm)
  - 1280 (12 μm)
  - 1024 (12 μm)
  - 1024 (12 μm)

- **Dynamic range**
  - 12° (25 e/s)
  - 12° (25 e/s)
  - 12° (25 e/s)
  - 12° (25 e/s)

- **Monochromator**
  - SiO₂ (2 keV)
  - SiO₂ (2 keV)
  - SiO₂ (2 keV)
  - SiO₂ (2 keV)

- **Repetition rate (Hz)**
  - 120
  - 120
  - 2000
  - 1000

- **X-ray optics in experimental hutch**
HED Instrument Parameters for Early User Operation

All parameters are subject to change, depending on the commissioning process of both the accelerator and the instrument.

For more information, please contact:
ulf.zastrau@xfel.eu

**X-Ray Photon Beam Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy</td>
<td>9 keV</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>0.5 – 1 mJ</td>
</tr>
<tr>
<td>Photons per pulse</td>
<td>$3 \times 10^{11}$</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>10 fs</td>
</tr>
<tr>
<td>Spot size on sample</td>
<td>$\text{min. } 1 \mu m$</td>
</tr>
<tr>
<td>Photons/µm² on sample</td>
<td>$10^{5} - 10^{10}$</td>
</tr>
<tr>
<td>Train repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Intra-train repetition rate</td>
<td>1.1, 4.5 MHz</td>
</tr>
<tr>
<td>No. of bunches per train</td>
<td>1-60</td>
</tr>
<tr>
<td>$\Delta E/E$</td>
<td>$\sim 0.2%$</td>
</tr>
</tbody>
</table>

**Detectors**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ePix100</th>
<th>ePix10k</th>
<th>Jungfrau</th>
<th>Gotthard-I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor</td>
<td>SLAC</td>
<td>SLAC</td>
<td>PSI</td>
<td>PSI</td>
</tr>
<tr>
<td>Sensor size</td>
<td>300 µm Si</td>
<td>300 µm Si</td>
<td>320 µm Si</td>
<td>320 µm Si</td>
</tr>
<tr>
<td>Pixel size</td>
<td>50</td>
<td>100</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$10^2$ (µs)</td>
<td>$10^4$ (µs)</td>
<td>$10^4$ (µs)</td>
<td>$10^4$ (µs)</td>
</tr>
<tr>
<td>Noise (eV)</td>
<td>&lt;280</td>
<td>&lt;560</td>
<td>&lt;450</td>
<td>&lt;900</td>
</tr>
<tr>
<td>Repetition</td>
<td>120</td>
<td>120</td>
<td>2,000 *</td>
<td>40,000 **</td>
</tr>
<tr>
<td># of modules</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

* 0.5 MHz in burst mode, 16 images on-chip memory
** 0.8 MHz in burst mode, 128 images digital memory

**Spectrometers (diagnostics and experimental)**

- **Single Shot Spectrometer (CAEP)**
  - Crystals: 4x10 µm Si
  - Energy: 3-15 keV with grating 5-25 crystal only
  - Energy resolution ($\Delta E/E$): $<1 \times 10^{-4}$
  - Detector: Optical CCD (2D)
  - Gotthard-I (1D)
  - Detector arm rotation: 30° - 90°

- **Experimental (Analyzer crystals for IXS and hrIXS)**
  - 4 high resolution diced analyzers: Si 533, 10 mm diameter, $R = 1$ m spherical
  - 2 mosaic spectrometers: HAPG 002, $R^*$ 50 and 75 mm, cylindrical 32 mm x 30 mm size

**Monochromators**

- **X-ray bandwidth**
  - High precision positioning system: SASE, 10^-3 - 25 keV
  - S_11, mono: 10^-4 - 5-25 keV
  - S_26, high-res mono: 10^-4 - 7.494 keV

**Target delivery**

- **Target system**: High precision positioning system
  - Rep rate: Shot on demand
  - Fast Sample Scanner: Foil, crystal, powder
  - Cryogenic jets: Solid H2, D2, HD, CH4, Ne, Ar
  - Cryogenic jets: 10 Hz

**Optical Laser Systems**

<table>
<thead>
<tr>
<th>Laser</th>
<th>λ (nm)</th>
<th>Max. Repetition Rate</th>
<th>Pulse Diffraction Energy</th>
<th>Max. Pulse Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>~ 800</td>
<td>0.1 – 4.5 MHz</td>
<td>15 – 300 fs fourier-limited</td>
<td>≤ 2 mJ</td>
</tr>
<tr>
<td>PP</td>
<td>1030</td>
<td>0.1 – 4.5 MHz</td>
<td>~ 1 ps</td>
<td>≤ 40 mJ</td>
</tr>
<tr>
<td>HI</td>
<td>~ 800</td>
<td>10 Hz</td>
<td>~ 25 fs</td>
<td>≤ 10 J</td>
</tr>
<tr>
<td>HE</td>
<td>515 (1030</td>
<td>1 – 10 Hz</td>
<td>15 ns or shorter</td>
<td>~100 J at 1030 nm</td>
</tr>
</tbody>
</table>

* Please inquire HED staff about availability
X-ray beam transport and properties at the High Energy Density science instrument at European XFEL

K. Appel¹, C. Baehz¹, B. Chen¹, T. Feldmann¹, S. Göde¹, Z. Konopkova¹, M. Makta¹, E. Martens¹, W. Morgenthal¹, M. Nakatsutsumi², A. Peik²
S. Roling³, A. Schmidt³, K. Suhanников³, I. Thorpe³, and U. Zastrau¹

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⁴ Frankfurt University, Germany, ⁵ Münster University, Germany

Abstract

The HED science instrument is located at the SASE2 undulator, which produces hard X-rays in an energy range between 3 and 25 keV. The first 390 m downstream of the undulator source are shared with the scientific instrument MID [1]. A distribution mirror is located at 390 m that allows to stir the beam to the HED science instrument which is located in the experimental hall at about 970 m from the source [2, 3, 4]. As additional optical elements we foresee two monochromators, a split and delay unit, a quarter wave plate and four positions for focusing optics in the tunnel and in the experimental hall. This leads to a variety of X-ray beam properties at the sample position, that can be selected for the respective experiment. Major X-ray beam diagnostics in the HED part of the beamline comprise on-line monitoring of the arrival time of X-rays and optical lasers [5], an in-situ single-shot X-ray spectrometer combining a diamond grating with a convex Si crystal following the concept of [6], as well as intensity and position monitors.

XRFEL beam properties

SASE2 undulator

- Hard X-ray source: 3 – 25 keV photon energy, 10⁻² SASE bandwidth, 10⁻⁵ self-seeded
- Repetition rate: 10 kHz bunch trains with up to 2700 pulses, pulse on demand
- Pulse energy: 10⁻¹ – 10⁻² X-ray photons per pulse / 100 nJ – few mJ
- Pulse duration: 2 to 100 fs (correlates with bunch charge)

10 Hz burst

0-2700 pulses/bunch

Top, left: Schematic top view of the six first scientific instruments at European XFEL. Top, right: Pulse picker for HED (rotating disk, 10 Hz). Bottom: Schematic of the electron beam time structure.

Key X-ray beam diagnostics

- In-situ single shot spectrometer combining a diamond grating with a convex Si crystal
- In-situ fast intensity monitors based on back-reflection of diamond foils
- intensity monitors based on fluorescence screens
- Online monitoring of the arrival time between X-rays and optical lasers

Left: Concept of the single shot spectrometer with technical drawing: the spectrometer crystal can either be used in the direct beam at 10 Hz, or in the full pulse train using the grating. A intensity monitor for the diffracted beam is available. Right: Technical drawing and picture of the in-situ fast intensity monitor.

References

Sample stage at the HED: mount design and exchange system in vacuum

Standardized sample holder concept and load-lock exchange system

M. Makita¹, K. Appel¹, C. Baehitz², B. Chen⁴, C. Deiter¹, S. Di Dio Casilo³, T. Feldmann¹, S. Göde¹, M. Hassan⁵, H. Höppner⁶, Z. Konopkova¹, E. Martens¹, D. Möller¹, M. Nakatsutsumi⁷, A. Pelka², T. R. Preston¹, A. Schmidt¹, K. Sukharnikov⁸, I. Thorpe¹, M. Toncian¹, T. Toncian², and U. Zastrau¹

¹ European XFEL, Germany
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³ Chinese Academy of Engineering Physics, People’s Republic of China

Introduction

The HED instrument focuses on matter at extreme conditions of temperature, pressure, electric and / or magnetic field. The solid sample holder system employs the standardized design concept from the EUCALL project (proposal #654220) which consists of a two-part system:

(1) Inner sample frame: standardized outer dimension, and can be modified for specific sample geometry, and

(2) outer carrier frame: standardized inner dimension, with unique frame design permanently installed for each facility. The design serves different subsets of user communities to be able to prepare and fabricate samples that are physically compatible at every participating facilities.

Solid sample loading

- [Above] Load-lock schematic view
- Gate valve connection to the main interaction chamber (IC)
- Independent vacuum system to the chamber
- Positioning of exchanged sample is done with clamps, identification pins & fiducial markers
- Fast sample scanning x,y motors will be positioned on top of the Hexapod

Sample holder

- Standardized Sample frame & holders
  - (left): Example of the Outer frame.
  - (right): Inner frame, to fit the outer frame. 10cm x 10cm area. Within this dimension, the frame design, geometry and materials can be modified. The sample frame is compatible to those of the ELIMAIA beamline.

- [Below] Sample frame holder cassette
  - Holds up to ~8 samples at a time
  - Sample exchange and refilling without breaking the vacuum nor affecting the setup

Liquid Jet samples

- Liquid jets deliver debris-free samples at repetition rate of 10 Hz [3]
- Using cryogenic liquids provide new materials at solid density such as H₂, He, CH₄, CO₂, ...
- Jets with planar/flat geometries with variable thickness enabled controlled dynamic shock compression studies
- Laser driven protons from liquid H₂ jets may be applied for isochoric heating studies
- Development of a platform for routine application of liquid jet techniques at HED under investigation

Sample monitoring

- Long & short distance cameras to monitor the positioning of the sample
  - ~3 out-vacuum cameras (red sqs) position for long-range view
  - 2-3 in-vacuum cameras (orange sqs) for high resolution adjustment

Future developments

- Motor for high rep-rate (10Hz) experiments
- Scan speed, step-size requirements and limits
  - sample dimension (10 x 10 cm²) limits stepsizes for 10 Hz scanning
- Protection from energetic electrons generated from the intense pump dynamics
- Tolerance to EMP from the irradiated targets
- Installation of motor stage cooling system
- EMP tolerance test
- Planned experiment in Summer 2018 at HIBEF (Institute of Radioactive Physics, Helmholtz-Zentrum Dresden-Rossendorf)

Sample exchange arm design
- ~1 m long foldable mechanism
- Weight tolerance ~ kg.

1. C. Deiter et al. EUCALL Grant agreement number: 654220
2. I. Prncipe et al., H.P.L. Sci. and Eng. (submitted)
3. J. Kim, S. Göde et al., RSI 87, 11E328 (2016)
Abstract:
The HED instrument at the European XFEL offers the unique opportunity to develop new experimental capabilities to explore planetary physics of solar and extra solar planets using new static and dynamic DAC x-ray diffraction techniques. Within this poster we describe some of the current ideas to make optimal use of these DACs at the European XFEL and present the current status of the design for a DAC setup for the HED instrument funded within the HIBEF consortium.

Introduction:
Time resolved diffraction at simultaneous high-pressure and -temperatures as well as fast compression/heating is an emerging field in static/dynamic high-pressure physics. This technique may be used to determine Equation of State (EOS) and phase stability at very high pressures and temperatures using the double stage Diamond Anvil Cell (dDAC, Dubrovinsky et al. 2012) and the dynamic Diamond Anvil Cell (dDAC, Evans et al. 2007), which is not achievable with conventional static high-pressure techniques. In addition one may explore the effects of changing compression rates on the location and kinetics of solid-solid as well as solid-liquid phase transitions using the dynamic Diamond Anvil Cell (dDAC). While dynamic compression-diffraction experiments are possible at 3rd generation sources in the kHz (μs) regime, it will require new 4th generation sources, such as the European XFEL, to be able to conduct time resolved experiments in the kHz (ns) regime. Since July of 2015 we have been developing a DAC setup for the “Helmholtz International Beamline for Extreme Fields” (HIBEF) user consortium lead by HZDR and DESY. Below we describe the current status of the design for the DAC setup to conduct time resolved dynamic compression experiments in the dDAC and sDAC.

Fig. 1 Left: Schematic description of the double stage setup used by Dubrovinsky et al. (2012). Right: Conceptual experimental setup for conducting dDAC experiments and laser heating using a 3 µs laser heating pulse and the 4 MHz repetition rate of the XFEL for collecting diffraction images. One may attribute 22 diffraction images over approximately 5 ns total exposure time for data taken in the effect of volumetric heating when using a very small x-ray beam (see Fig. 3).

Fig. 2: Top: schematic of the DAC vacuum vessel to be placed at the IG for combined DAC/SX experiments. Bottom: trade-off of the x-ray detector. dDAC setup.

Fig. 4: Top: Current design of the DAC vacuum vessel to be placed at the IG for combined DAC/SX experiments. Bottom: trade-off of the x-ray detector. dDAC setup.

Fig. 3: Conceptual design of the double stacked plate laser heating system for the DAC setup for the HED instrument.

References: